3D-CT MEASUREMENT OF AN INSTANTANEOUS DENSITY DISTRIBUTION OF A TURBULENT PREMIXED FLAME WITH A MULTI-DIRECTIONAL QUANTITATIVE SCHLIEREN CAMERA

Y. Ishino, T. Kato, Y. Kurimoto and Y. Saiki

Nagoya Institute of Technology

ishino@nitech.ac.jp

1 Introduction

In previous works (Saiki et al. (2010)), 3D-CT (Three Dimensional Computer Tomography) reconstruction of instantaneous 3D light emission distributions of turbulent premixed flames have been successfully obtained by a simultaneous photography with a custom-made 40-lens camera. Furthermore time-series 3D-CT distributions have been reconstructed by using a single high speed camera combined with a multi-mirror optical system (Ishino et al. (2011)). The techniques, in which light emission from target was captured, however, had an essential disadvantage for high speed detection of flames in terms of the shortage of the quantity of light, resulting in blurring image.

In present study, in order to provide a suitable technique for 3D observation of high speed turbulent flames, non-scanning 3D-CT technique using a multi-directional quantitative schlieren system with flash light source, is proposed for instantaneous density distribution of unsteady premixed flames. This "Schlieren 3D-CT" is based on (i) simultaneous acquisition of flash-light schlieren images taken from numerous directions (see fig.1), and (ii) 3D-CT reconstruction of the images by an appropriate CT algorithm. In this paper, first, as a preliminary research, 3D-CT reconstruction of non-axisymmetric steady flame is made with a single-directional quantitative schlieren system. Next, with custom-made 20 directional schlieren camera, an instantaneous density distribution of a high-speed turbulent flame, which can be used as an industrial furnace burner flame, has been CT-reconstructed.

2 Experimental apparatus and method

2.1 Target Flame and Coordinate System

The target steady flame, as shown in fig.2(a), is a

![Figure 1: Schematic of 20-dir. schlieren camera.](image1)

![Figure 2: Burner and target flames.](image2)
non-axisymmetric steady premixed flame group combining three conical flames having different sizes anchored on burner tip with three nozzles of different diameters of 5.0 mm, 4.0 mm and 3.0 mm. The propane-air premixed gas of equivalence ratio of $\phi = 1.1$, is issued from the nozzles. The average flow velocity at the nozzle exits is set to 2.5 m/s.

Next, the target turbulent flame is indicated in fig. 2(b). The burner has a nozzle exit of 4.2 mm diameter. The average flow velocity of the propane-air mixture of equivalence ratio of 1.1 is set to be 10.0 m/s ($Re = 3151$). The burner is equipped with a turbulence promoting orifice in the burner tube. In order to anchor the high-speed flame on the burner nozzle, the burner tip has 4 holes for introducing the pilot flames.

2.2 Schlieren System

Figure 3 depicts the single-directional quantitative schlieren system used for investigation of target steady flame. This system is composed of two convex achromatic lenses of 50 mm in diameter and 300 mm in focal length, a light source unit, a schlieren stop of a vertical knife edge and a digital camera. The light unit has a flash light source of a uniform luminance rectangular area of 1 mm $\times$ 1 mm. Both of the uniformity of the luminosity and the definite shape are essential for a quantitative schlieren observation. Sensitivity of the camera is calibrated with a stepped neutral density filter. This schlieren system is located in ambient air of the density $\rho_a = 1.2$ kg/m$^3$ so as to ensure the continuity of gas density at boundary of observed area. To capture multi-directional views on a stationary optical system, the burner tip is revolved in the 40 angle positions from $\theta = -87.75$ to 87.75 deg. at interval of 4.5 deg. with a turning table.

Figure 4 shows the custom-made 20-directional schlieren camera, which consists of 20 systems of above-mentioned single-directional quantitative schlieren system. The flash lights of 14 $\mu$s duration are employed as light source to get still images of high speed flame. In the present study of vertical flames, the camera position is set to horizontal position as shown in fig.4(a). The camera position can be converted from horizontal position to vertical(fig.4(b)).

2.3 Conversion Procedure of Images

In the proposed schlieren 3D-CT system, 3D-CT process requires 2D distribution (image) of the "deviation density thickness", which is defined by the line-of-sight-integration of density deviation from ambient gas density. The 3D-CT process in this investigation is not made in the three dimensional manner, but that is accomplished by stacking 2D density distributions. On each horizontal plane over observed height range, the density distributions are reconstructed from linear distributions of deviation density thickness $Dt(\chi(\theta))$, called "projections", of numerous directions ($\theta$). Here the procedure for obtaining the deviation density thickness distribution $Dt(\chi(\theta))$ from a schlieren image, is explained as

![Figure 3: Single quantitative schlieren system.](image-url)

![Figure 4: The 20-directional schlieren camera.](image-url)
follows. Figure 5 indicates the conversion process of image data. Figure 5(a) depicts density distribution \( \rho^*(x, y) \) having an ambient gas (air) region of constant density \( \rho_a^* \) on peripheral of observed range of radius \( R \). This configuration is consistent with the characteristics of stand-alone flames.

Figure 5(b)-(h) show observations in the direction of \( \theta \) from \( x \)-axis. The inclined coordinates are denoted by \( X(\theta) \) and \( Y(\theta) \) as indicated in fig.5(a). For reference, fig.5(c) gives the deviation density on the line of sight

\[
\Delta \rho^*(X(\theta), Y(\theta)) = \rho_a^* - \rho^*(X(\theta), Y(\theta))
\]

where \( \rho_a^* \): the density of ambient gas, \( \rho^*(X(\theta), Y(\theta)) \): the density of gas. Because of lower density of burnt gas, deviation density has non-negative value in all region. The deviation density \( \Delta \rho^*(X(\theta), Y(\theta)) \) is spatially-integrated automatically along line of sight in schlieren observation, resulting in density thickness \( Dt^*(X(\theta)) \) of fig.5(d).

Brightness of schlieren image \( B(X) \) is given as \( X \)-directional gradient value of density thickness \( Dt^*(X(\theta)) \) shifted by brightness of no-flame image \( B_{nf}(X) \), indicated in fig.5(e).

Schlieren observation only presents \( B(X) \) and \( B_{nf}(X) \). To obtain the density thickness \( Dt^*(X(\theta)) \) from \( B(X) \) and \( B_{nf}(X) \), both are processed in the following manners of fig.5(f)-(h). As indicated in fig.5(f) and(g), deviation brightness in schlieren image

\[
\Delta B(X) = B(X) - B_{nf}(X)
\]

is scaled to \( d(Dt)/dX \) by next expression

\[
d(Dt)/dX = - (1/K)(\Delta s/f)(\Delta B(X) / B_{nf}(X))
\]

where \( K \) is Gladstone-Dale constant for air(\( K = 2.26 \times 10^{-4} \) m³/kg), \( \Delta s \) is transparent width of light source image on schlieren stop location and \( f \) is the focal length of convergent lens. Deviation density thickness \( Dt^*(X(\theta)) \) is, therefore, reproduced by transverse-integration of \( d(Dt)/dX \) from schlieren images, as shown in fig.5(h).

2.4 CT Reconstruction

MLEM method (Saiki et al.(2010) and Ishino et al.(2011, 2013a, 2013b)) is employed for CT reconstruction. The CT procedure is carried out in each horizontal plane of \( z \) for reconstruction of deviation density distribution \( \Delta \rho(x, y) \) from linear data set of deviation density thickness \( Dt^*(X(\theta)) \). This reconstructed deviation density distribution \( \Delta \rho(x, y) \) is converted to 2D density distribution \( \rho(x, y) \) as follows.

\[
\rho(x, y) = \rho_a^* - \Delta \rho(x, y)
\]

The 2D distributions \( \rho(x, y) \) is accumulated in layers to form 3D-CT distribution \( \rho(x, y, z) \).

3 Result and Discussion

3.1 Steady flame

First schlieren-CT reconstruction has been conducted for a target steady flame, as following manner. Figure 6 indicates eight samples of 40 multi-directional quantitative schlieren images with shifted brightness of no-flame image; \( B(X, z) \) in fig.5(e). These images are processed by the conversion procedure of chapter 2.3 to projection
images of density thickness $Dt(X(\theta))$, as shown in fig.7.

Three dimensional density distribution, reconstructed by 3D-CT from projection images of deviation density thickness $Dt(X(\theta), z)$, is presented in fig.8 and 9. Figure 8 gives nine samples of horizontal ($z$-plane) density distributions. Figure 9 also shows twelve samples of vertical ($y$-plane) density distributions. Positions of each distribution is denoted by lines in fig.8(i) and fig.9(e). Horizontal distribution, for example, exhibits three high density circular region correspondent with unburnt inner regions of each conical flame within burnt gas region of low density. Triangle regions of high density are observed in vertical distributions in fig.9. These observed characters show excellent agreement with characteristics of the target steady flame structure.

3.2 Turbulent flame

In this investigation, schlieren-CT reconstruction
of the target turbulent flame has also been conducted.

First, 20-directional schlieren images of the target turbulent flame are simultaneously taken with the multi-directional schlieren camera. Next, brightness of no-flame images are subtracted from the schlieren images to obtain the quantitative schlieren images of fig.10. The deviation density thickness images are also calculated as fig.11.

Using the deviation density thickness images as projections for CT reconstruction, 3D instantaneous distribution of turbulent premixed flame has been successfully obtained for $z = 8.5 - 40 \text{ mm}$, as shown in fig.12. In fig.12, horizontal(a-f) and vertical(g, h) cross-sectional distributions of density are indicated. The distribution shows the complicated shape of the high speed turbulent flame. Figure 12 gives the information of 3D-bird's eye views of the 3D-CT data. The density of 0.7 $\text{kg/m}^3$ is selected as a threshold level. The left figure is the view from x-coordinate, the right from y-direction. In the figures, nozzle image are inserted, also, the top surfaces ($z = 8 \text{ mm}$) of the outer glass pipe(16 mm outer dia.) are depicted for reference. The views clearly gives the information of the flame structure with fine scale corrugations.

### 4 Concluding Remarks

In this paper, 3D-CT reconstruction of a steady flame was made with a single-directional quantitative schlieren system. CT reconstruction of instantaneous density distribution of a high-speed turbulent premixed flame has been successfully obtained.

### Acknowledgements

This research work was partly supported by JSPS Grants-in-Aid for Scientific Research (C)23560226.

### References

Ishino, Y. et al. (2011), 4D-CT measurement of a turbulent premixed flame by simultaneous multi-directional high-speed photography with multi-mirror optical capture system, *Proc. of Int. Symp. on EcoTopia Science’11*.

Ishino, Y. et al. (2013a), Multi-Directional Quantitative Schlieren Observations for 3D-CT


Saiki, Y. et al. (2010), Measurement of a local burning velocity of a turbulent premixed flame by simultaneous 3D-CT reconstruction with 40-Lens camera and stereoscopic PTV, *Proc. of 8th ETMM*.